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A coupled modelling approach to assess the effect of fuel treatments on post-wildfire runoff and erosion

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Abstract. The hydrological consequences of wildfires are among their most significant and long-lasting effects. As wildfire severity affects post-fire hydrological response, fuel treatments can be a useful tool for land managers to moderate this response. However, current models focus on only one aspect of the fire–watershed linkage (fuel treatments, fire behaviour, fire severity, watershed responses). This study outlines a spatial modelling approach that couples three models used sequentially to allow managers to model the effects of fuel treatments on post-fire hydrological responses. Case studies involving a planned prescribed fire at Zion National Park and a planned mechanical thinning at Bryce Canyon National Park were used to demonstrate the approach. Fuel treatments were modelled using FuelCalc and FlamMap within the Wildland Fire Assessment Tool (WFAT). The First Order Fire Effects Model (FOFEM) within WFAT was then used to evaluate the effectiveness of the fuel treatments by modelling wildfires on both treated and untreated landscapes. Post-wildfire hydrological response was then modelled using KINEROS2 within the Automated Geospatial Watershed Assessment tool (AGWA). This coupled model approach could help managers estimate the effect of planned fuel treatments on wildfire severity and post-wildfire runoff or erosion, and compare various fuel treatment scenarios to optimise resources and maximise mitigation results.

Additional keywords: AGWA, Bryce Canyon National Park, fire effects, watershed, WFAT, Zion National Park.

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Introduction

The increase in large damaging wildfires in the western US in recent decades has engaged the attention of scientists, federal agencies, policy makers and the public, who increasingly agree on the need to move away from total suppression (GAO 2007; GAO 2009; Stephens *et al.* 2013). As most dry forests in the US were historically prone to frequent, low-intensity fires, fuel treatments have emerged as a potential supplement to suppression (Allen *et al.* 2002; Graham *et al.* 2004; GAO 2007; Fulé *et al.* 2013).

Although direct effects of wildfires on vegetation are often the focus of public attention, post-fire flooding and erosion can be one of the most damaging effects of wildfires on the landscape. Peak discharge can increase following a fire for a variety of reasons, whereas water yield may increase but less dramatically (Anderson *et al.* 1976; Canfield *et al.* 2005; Moody *et al.* 2013). Vegetation cover is greatly reduced and hydrophobic soils can form, causing decreased interception and infiltration, which lead to an increase in runoff and erosion during a precipitation event (Robichaud *et al.* 2000; DeBano 2003).

There is evidence that pre-wildfire fuel treatments can indirectly mitigate post-fire runoff and erosion (Anderson *et al.* 1976; Wohlgemuth *et al.* 1999; Loomis *et al.* 2003; Meixner and Wohlgemuth 2004). If fuel treatments can be successful in reducing post-fire runoff and erosion by moderating fire severity, this may be a more cost-effective solution than spending large sums fighting wildfires and then mitigating high-fire severity areas after the wildfire occurs to prevent flooding and severe erosion.

Although fuel treatments can take many forms, the most common types used on public lands are prescribed fire and mechanical thinning (GAO 2007). Prescribed burning is used to facilitate the reintroduction of fire into an ecosystem in a way that can be controlled and limited in fire intensity. Mechanical thinning involves removal of understorey trees, spreading of surface fuels and thinning of the crown layer in order to lessen the load and continuity of fuels in a forest. Both methods have proven to be locally successful in reducing the intensity of wildfires, with concomitant reductions in fire severity (Agee and Skinner 2005; Martinson and Omi 2013; Kennedy and Johnson

2014). However, despite large increases in investment into fuel treatments, the amount of treated area within forests in the US is still not sufficient to limit fire severity on a large scale (North et al. 2012). Scientists have recommended treating even larger areas in the future, which may increase the importance of fuel treatments in national fire policy (Stephens et al. 2013).

Modelling fuel treatments, wildfire and post-fire hydrological response

Models can help land managers simulate and visualise the effects of treatments, and their potential influence on fire severity and post-fire hydrological response. One non-spatial model that simulates fuel treatments is FuelCalc, which calculates initial forest fuel characteristics from forest inventory data and allows users to select specific treatments to apply to a particular stand. It then outputs post-treatment fuel characteristics, which can then be input into fire simulation models if desired (Heward et al. 2013).

The most widely used fire effects model is the First Order Fire Effects Model (FOFEM). FOFEM uses fire behaviour inputs along with forest inventory data, including tree density, species, tree height, diameter-at-breast-height (DBH) and canopy class, to model tree mortality, fuel consumption, smoke emissions and soil heating (Reinhardt 2003; Lutes 2013). The Wildland Fire Assessment Tool (WFAT) couples and runs FOFEM and FlamMap, a fire behaviour model, in a GIS environment. WFAT requires users to supply the raster layers needed to run FlamMap along with a layer of tree characteristics needed in FOFEM to model fire effects. The tool runs FlamMap to obtain the necessary fire behaviour inputs for FOFEM before running FOFEM and FuelCalc (Tirmenstein et al. 2012).

Several models exist to predict the effects of post-fire runoff and erosion. The Water Erosion Prediction Project (WEPP) is a process-based model that focuses on erosion processes for single hillslopes and small watersheds (Larsen and MacDonald 2007). The Erosion Risk Management Tool (ERMiT) is an erosion prediction tool widely used for post-fire modelling, allowing for the determination of sediment yield probabilities at the hillslope level (Robichaud et al. 2007). The tool uses WEPP to provide these probabilities based on variability in weather, fire effects and distribution of fire severity (Robichaud et al. 2007).

Although the above models are useful for predicting post-fire erosion at a hillslope or small watershed scale (<100 ha), a model that can treat larger watersheds and predict runoff and erosion across several scales (hillslope to large watershed) would be a useful planning tool. The Kinematic Runoff and Erosion Model (KINEROS2) is a physically based event-driven hydrological model that is usable in a GIS interface by its inclusion in the Automated Geospatial Watershed Assessment tool (AGWA; Semmens et al. 2007; Goodrich et al. 2012). AGWA incorporates KINEROS2 into GIS by automating certain processes and running the model on all hillslopes and channels within a delineated watershed.

Although these models have many uses independently, coupling them offers a new method not currently realised to predict how pre-wildfire fuel treatments affect post-wildfire hydrological response. Linked or coupled models are used widely in ecology when no single platform is likely to be adequate to address all potential research applications (Foley et al. 1998). Such a modelling approach is outlined in this study, linking FuelCalc, FOFEM and KINEROS2 in order to give land managers a way to model planned fuel treatments, wildfire and post-fire hydrological effects together (Fig. 1). We demonstrate this modelling approach in case studies at Zion and Bryce Canyon national parks.

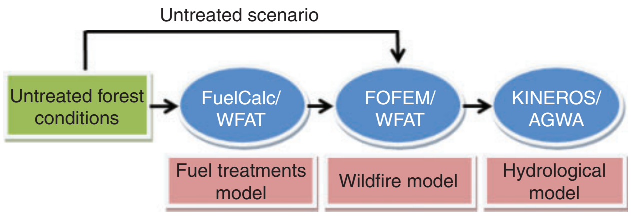

Fig. 1. Modelling process.

Methods

Study sites

Zion and Bryce Canyon national parks are located in south-western Utah, USA, within the Temperate Desert Mountains ecoregion as defined by Malamud et al. (2005). In south-western Utah, most fires occur during the hot, dry summer months, which are followed by late summer monsoon thunderstorms (National Park Service 2004). Both parks are within the Arizona rainfall type with the medium-intensity condition defined by Moody and Martin (2009), having a 2-year 30-min rainfall intensity of 20–36 mm hr^{-1}. The hydro–geomorphic regime of Zion National Park is characterised by steep slopes and easily eroded soils. Bedrock and slickrock exposures are common (National Park Service 2004). Deep, narrow slot canyons can carry rapid flash floods as a result of these conditions. Bryce Canyon is characterised by a forested plateau above cliffs and tower formations of exposed sandstones and shales. These formations are very steep and highly erodible, which can lead to large sediment yields during rain events (Kelletat 1985; Doremus and Kreamer 2000).

The modelled watershed in Zion includes Wildcat Canyon at the north edge of the park, which drains into the Right Fork of North Creek (Fig. 2). The outlet of the watershed is within a slot canyon in North Creek ~2.5 km downstream from the outlet of Wildcat Canyon. The watershed covers 2297 ha, with elevations ranging from 1704 to 2492 m above sea level. This watershed was selected for study because it includes the location of a planned prescribed burn. The burn area is in the northern section of the watershed and includes ~460 ha (~20% of the watershed) of mixed forest types including white fir (*Abies concolor*), pinyon–juniper (*Pinus monophylla*, *Pinus edulis–Juniperus osteosperma*), quaking aspen (*Populus tremuloides*), ponderosa pine (*Pinus ponderosa*) and gamble oak (*Quercus gambelii*; Zion National Park 2009). Much of the area's current forest conditions are more overgrown than historically, due to over a century of fire suppression efforts (National Park Service 2004). The park's goals for the prescribed fire include limiting fire spread into the wildland–urban interface, improving vegetation species diversity and providing benefits to wildlife (Zion National Park 2009).

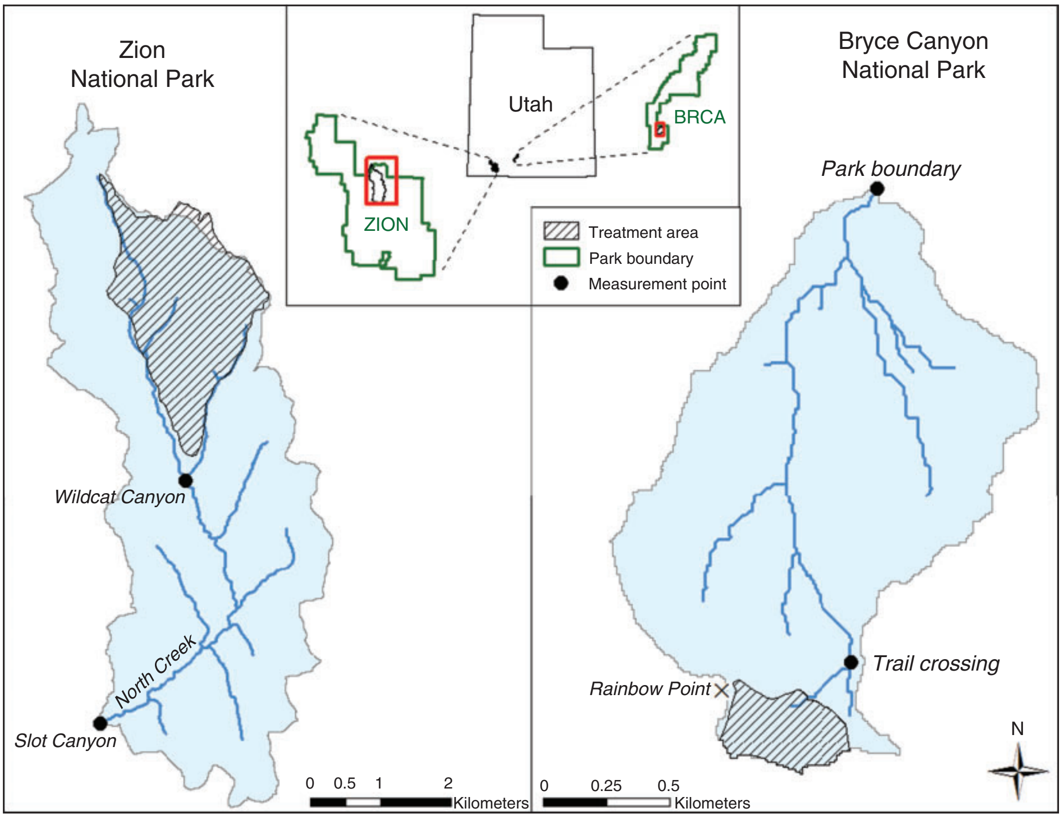

Fig. 2. Location of study sites.

The modelled watershed in Bryce Canyon is at the southern end of the park near Rainbow Point lookout (Fig. 2). The watershed outlet is at the park boundary and it drains into Willis Creek, part of the larger Paria River watershed. The watershed is 216 ha in area, and ranges in elevation between 2306 and 2778 m above sea level. Park staff have identified 12.51 ha of the upper part of this watershed (~6% of the entire watershed) for a mechanical thinning treatment. The treatment area is above the plateau rim and includes thick, mixed conifer forest. The park's goal for the thinning project is to reduce hazardous fuels that would support extreme fire behaviour in and around heavily visited areas that contain several historical structures (Brothwell 2012).

Modelling fuel treatments

Prescribed fire at Zion

WFAT was used to simulate the prescribed fire in Wildcat Canyon in Zion. The spatial topography and fuel input layers necessary to run the model were obtained from LANDFIRE (LF; available at http://www.landfire.gov/; Rollins, 2009). Fuel inputs included canopy base height, canopy bulk density, canopy cover, canopy height, fire behaviour fuel model (FBFM) and fire effects fuel model (FEFM). The National Tree List Layer (NTLL) was also used as an input into WFAT. NTLL contains the information necessary for FOFEM to calculate tree mortality (Drury and Herynk 2011). The NTLL makes use of the LF-Reference Database, a database of geo-referenced field data for forest fuels used to compile LF layers within the US.

Table 1. WFAT Input weather parameters for modelled prescribed fires

Values come from the Wildcat Prescribed Burn Plan (Zion National Park 2009)

Parameter	Value
Relative humidity (%)	20
6-m windspeed ($m\,s^{-1}$)	4.47
Wind direction (degrees)	247
1-h fuel moisture (%)	6
10-h fuel moisture (%)	6
100-h fuel moisture (%)	10
Woody live fuel moisture (%)	80
Herbaceous live fuel moisture (%)	80

Weather conditions for the prescribed fire were set according to the Weather and Fuel Guidance Parameters, as specified by the desired prescribed fire intensity conditions in the Wildcat Prescribed Burn Plan (WPBP; Table 1; Zion National Park 2009). To input these weather conditions in WFAT, fixed fuel moisture files were created and used for the fire simulation (Tirmenstein *et al.* 2012). Fuel moistures from the WPBP for 1-h, 10-h, 100-h, live herbaceous and live woody fuels were used.

After the prescribed burn was simulated using existing fuels, WFAT input layers were altered to represent the treated landscape. The input layers obtained from LF were altered or 'treated' by WFAT in the prescribed burn simulations automatically, and were output by the tool. Preparing the tree list layer for wildfire simulation required manual alterations because a treated tree list layer is not an output of WFAT. This required manipulating the tree list database outside the GIS interface using the percentage mortality output layer from the WFAT prescribed burn simulation, which provided the percentage of trees killed within each cell. In order to remove all the killed trees from the tree lists, enough trees were removed from each tree list to match the percentage mortality value for that cell. To select which trees to remove from the tree lists for cells that experienced partial mortality, it was assumed that the prescribed fire killed the smallest diameter trees first. This assumption is supported by multiple studies that have shown DBH to be negatively correlated with tree mortality, especially when used as a surrogate for bark thickness and canopy height (Harrington 1987; Ryan and Reinhardt 1988; Stephens and Finney 2002; Hull Sieg *et al.* 2006).

Mechanical thinning at Bryce Canyon

Since WFAT did not include the mechanical thinning functionality of FuelCalc at the time of this study, tree list manipulation and the stand-alone non-spatial version of FuelCalc were used to model the planned mechanical treatment at Bryce Canyon. Tree lists from NTLL were input into the model, which calculated pre-treatment stand measurements corresponding to LF layers for canopy bulk density, canopy base height, canopy cover and FBFM. The mechanical thinning treatment applied was a simplified version of the methods described in the Rainbow Point Mechanical Fuel Reduction Plan (Brothwell 2012). This involved altering, or 'thinning' all tree lists that had >40 stems per hectare to below that threshold, deleting from the tree lists all the smallest trees with a DBH <20.3 cm (8 in) first. Once this treatment was applied, the treated tree lists were placed back into FuelCalc to calculate post-treatment stand characteristics.

Modelling wildfire with WFAT

In order to evaluate the effect of fuel treatments on wildfire severity, we modelled wildfires on both untreated and treated landscapes. Wildfires on the untreated landscapes in both parks used unaltered LF 2008 and NTLL layers for spatial inputs into WFAT. For the wildfire on the treated landscape in Zion, the output layers from WFAT following the prescribed fire simulation and the manually-altered NTLL tree lists were used. For the wildfire on the treated landscape in Bryce Canyon, the LF layers needed to be altered manually because the mechanical thinning treatment could not be simulated within WFAT. FuelCalc calculates values such as canopy bulk density and canopy base height directly from the input tree list. As these values are also available from LF layers, it was possible to compare the calculated stand measurement values in FuelCalc from NTLL with those from LF. However, the pre-treatment stand measurement values derived from the NTLL tree lists in FuelCalc did not always match the values from the LF layers in the same location. Therefore, post-treatment stand measurement values could not be derived directly from the FuelCalc results to create post-treatment spatial layers. Instead, the percentage change from the pre- to post-treatment stand measurements recorded by FuelCalc from the NTLL tree lists was applied to the pre-treatment LF layers to obtain spatial post-treatment layers. These created layers, along with the treated NTLL tree lists, were input into WFAT to model wildfire on a treated landscape.

All simulated wildfires were based on the weather conditions directly preceding recent wildfires at the two parks. For Zion, conditions preceding and during the 2006 Kolob Fire were used (National Park Service 2006). For Bryce Canyon, conditions for the 2009 Bridge Fire were used. In order to best represent the conditions in the study area preceding these fires, weather parameters were obtained from Remote Automated Weather Stations near the wildfire locations (Lava Point for Zion, Aqua Canyon for Bryce Canyon). WFAT allows fuel moistures to be 'conditioned' by weather variables preceding the simulated fire (Tirmenstein *et al.* 2012), which was done for the wildfires in this study. Conditioning variables included the daily precipitation totals, high and low temperatures, relative humidity percentages and wind characteristics for the 5 days preceding the two fires.

Two wildfires were modelled at each park; one covering the entire watershed, and another covering only the upper portion of the watershed (which in both cases included all of the treated area).

Modelling post-fire runoff and erosion with AGWA

The KINEROS2 model within AGWA was used to model all rainfall events in this study. Spatial inputs into AGWA included 10×10-m digital elevation models (DEMs) from the United States Geological Survey's (USGS) National Map (available at http://nationalmap.gov/viewer.html), STATSGO soil layers (available at http://websoilsurvey.sc.egov.usda.gov/) and park vegetation maps modified to fit National Land Cover Database classifications (available at http://www.usgs.gov/core_science_systems/csas/vip/index.html). AGWA alters KINEROS2 input parameters (Manning's n roughness coefficient, saturated hydraulic conductivity and interception) to represent a post-fire landscape by altering land cover based on burn severity (Canfield *et al.* 2005; Burns 2013). The Keane Severity Index (KSI) output from WFAT was used to create the fire severity layer used by AGWA to alter land cover values. KSI uses three fire effects outputs from FOFEM to create fire severity classes of low, moderate and high. Metrics include soil heating, tree mortality and fuel consumption (Keane *et al.* 2010). KSI is used as an index of fire severity in this study as it is a built-in output in WFAT and corresponds well with the definition of fire severity from Keeley (2009) as the loss of organic matter from above- and below-ground sources. All references to 'fire severity' in this study relating to WFAT outputs refer to the KSI directly.

At both study sites, rainfall events were modelled on three landscapes for each of the two wildfire scenarios: untreated and unburned, untreated and burned by wildfire, and treated and burned by wildfire. Two-year 30-min design storms were modelled on both sites to match typical monsoonal rains of southern Utah (13.6 mm rainfall depth in 30 min at Zion, 11.9 mm rainfall depth at Bryce Canyon). The 2-year 30-min storm has been suggested as an appropriate metric to use when examining post-fire hydrologic responses, since post-fire runoff and erosion can be significant even at low return intervals and short durations (Moody *et al.* 2013). The depth and durations of these storms were obtained from the online NOAA Atlas 14-point precipitation frequency estimates (National Oceanic and Atmospheric Administration 2013) using coordinates of the centroids of the watersheds. The storm was applied uniformly over the entire watershed using a SCS Type II intensity distribution built into AGWA (Burns 2013). Although monsoonal thunderstorms are typically not spatially uniform over watersheds of this size (Goodrich *et al.* 2008), this assumption treats the entire watershed equally from the perspective of rainfall inputs. This enables park managers to focus on assessing the effects of treatments and wildfires without the compounding complication of storm location and movement. The implications of this assumption are explored in more detail in another study in this special issue (Sidman *et al.* 2014).

Results and discussion

Fuel treatments

Both modelled fuel treatments clearly changed stand characteristics within the treatment areas (Fig. 3). The prescribed burn at Zion affected a wide range of characteristics, altering canopy base height, canopy cover, canopy bulk density and tree density, and changing the canopy height and fuel loading models (FLM) in some areas. Mechanical thinning at Bryce Canyon did not change canopy height or FLM, because by design, the treatment did not remove any large trees that control the canopy height and did not remove or add any ground fuels. Another difference between the two treatments was that the prescribed burn (Zion) increased areas of non-forested land, whereas the mechanical thinning (Bryce) did not. This is because the prescribed burn consumed all trees in some areas, rendering them non-forested by the model. The mechanical thinning, however, reduced only tree density, never removing all the trees from an originally forested area.

The untreated landscape in Bryce Canyon had a higher percentage of area with denser forest than Zion: 91% of Bryce Canyon's treatment area had canopy base heights of 0–0.9 m, and 87% had more than 300 trees per hectare (Fig. 3). Bryce Canyon's mechanical thinning was focused on reducing the density in those denser areas, while ignoring the less-dense areas. The post-treatment landscape represents this aim. The mechanical thinning reduced areas with a canopy base height of 0–0.9 m down to 45% of the total treatment area, and removed all areas with more than 300 trees per hectare. It also reduced area with a canopy bulk density of $\geq$0.10 kg m^{-3} from 34% pre-treatment to only 12% post-treatment.

Zion's treatment area had lower initial forest density. Only 20% of the area had canopy base heights of 0–0.9 m and 50% of the area had >300 trees per hectare. The prescribed burn influenced the treatment area more uniformly than the mechanical thinning, affecting both the dense and sparse areas. The burn reduced areas with a canopy base height of 0–0.9 m from 20% to 10% of the treatment area, and areas of 1.0–1.9 m from 25% to 17%. Prescribed fire did not completely eliminate areas with >300 trees per hectare, reducing those areas from 50% to 33%. However, the increase in non-forested land shows that some of the sparser areas were burned and some dense areas burned with high intensity. Ninety-six percent of the prescribed burn area

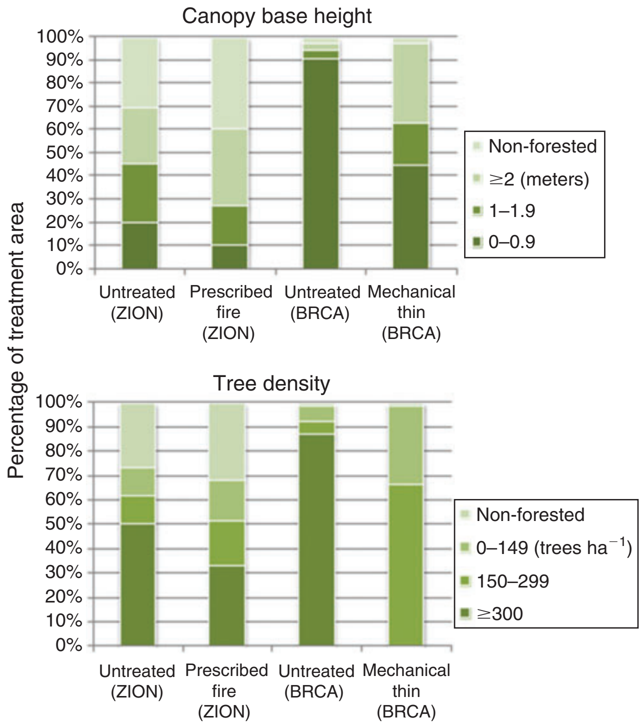

Fig. 3. Comparison of pre- and post-treatment landscapes.

with <150 trees per hectare resulted in at least low burn severity, while ~20% of areas with >300 trees per hectare resulted in high burn severity.

Wildfire

The two fuel treatments had different effects on subsequent wildfires that burned over the areas in which they were implemented (Fig. 4). The prescribed burn increased the watershed's unburned area in both the entire watershed wildfire (3% increase) and the upper watershed wildfire (24% increase), whereas the mechanical thinning did not change unburned area at all (Table 2). This can be attributed to the fact that the prescribed fire completely consumed some areas of forest, rendering them unburnable by the wildfire. This was not the case for the mechanical thinning, which simply reduced stand density. The prescribed burn was more effective than the mechanical thinning at reducing high severity area for both wildfire scenarios, but the mechanical thinning did more to reduce moderate severity area in both wildfire scenarios. The larger decrease in high severity area caused by the prescribed burn is likely due to some of the high severity area in the untreated scenario becoming unburned in the treated scenario as it was burned at high severity during the prescribed fire.

By virtue of the ratios of treatment areas to wildfire sizes, the fuel treatments had less influence on the entire watershed wildfire than on the upper watershed wildfire. The prescribed fire reduced high severity in the entire watershed wildfire (20% treatment area per wildfire area) by 22%, whereas it was reduced by 39% in the upper watershed wildfire (45% treatment area per wildfire area). Similarly, the mechanical thinning reduced high

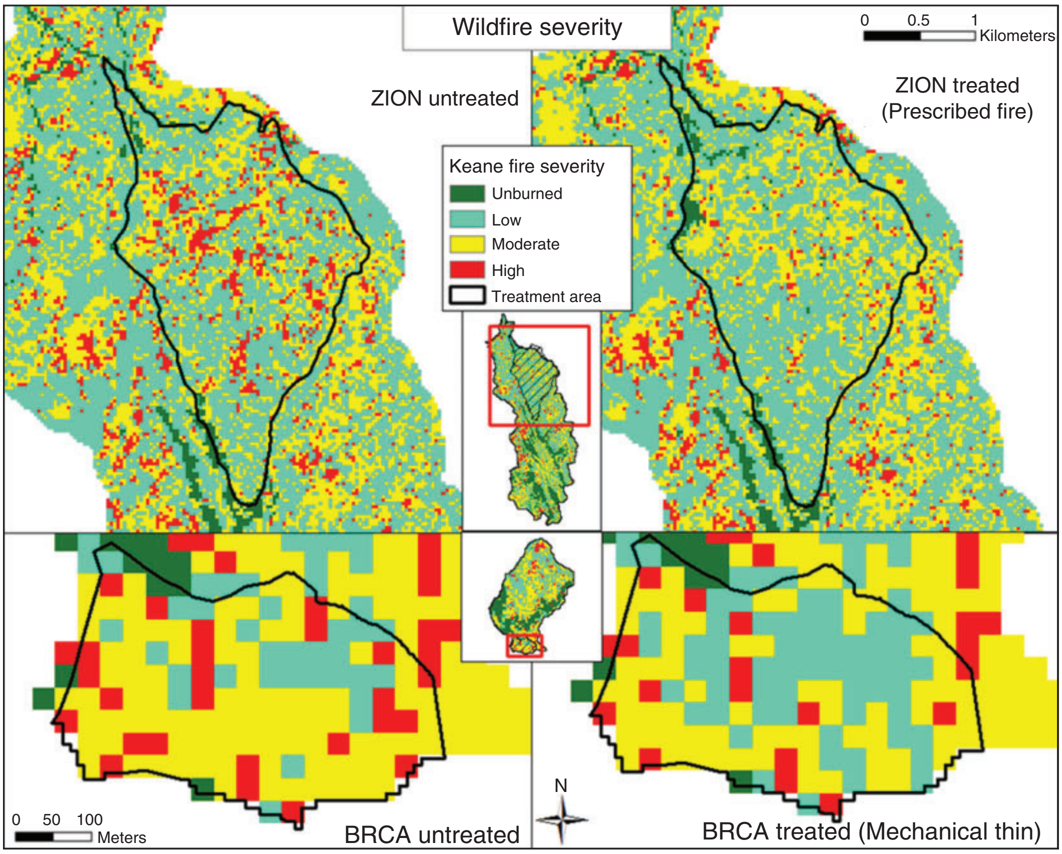

Fig. 4. Comparison of entire watershed wildfires on untreated and treated landscapes.

Table 2. Comparison of fire severity (KSI) between wildfires on untreated and treated landscapes

KSI	Untreated (ha)	Treated (ha)	% change	Untreated (ha)	Treated (ha)	% change
	Entire watershed wildfire					
	Zion (2297 ha)			Bryce Canyon (216 ha)		
Unburned	346.68	356.40	2.80	43.83	43.83	0.00
Low	935.37	955.35	2.14	64.08	66.78	4.21
Moderate	827.91	839.25	1.37	91.62	89.82	−1.96
High	186.84	145.80	−21.97	16.65	15.75	−5.41
	Upper watershed wildfire					
	Zion (1028 ha)			Bryce Canyon (28 ha)		
	Untreated (ha)	Treated (ha)	% change	Untreated (ha)	Treated (ha)	% change
Unburned	41.13	50.85	23.63	2.61	2.61	0.00
Low	535.41	555.39	3.73	5.04	7.74	53.57
Moderate	346.68	358.02	3.27	15.84	14.58	−7.95
High	105.12	64.08	−39.04	4.86	3.42	−29.63

severity in the entire watershed wildfire (5.9% treatment area per wildfire area) by 5% and in the upper watershed wildfire (45% treatment per wildfire area) by 29%. This is because the treatment areas make up a larger portion of the upper watershed wildfire areas than the entire watershed wildfire areas, increasing the effect of the treatments. Because of the random nature of wildfire ignition location and weather conditions, it is impossible to choose a 'best' or 'most realistic' wildfire extent when running WFAT. The comparison in this study of differing wildfire sizes simply points to the importance of modelling different-sized fires in order to gain a better understanding of the range of outcomes that are possible in a given area.

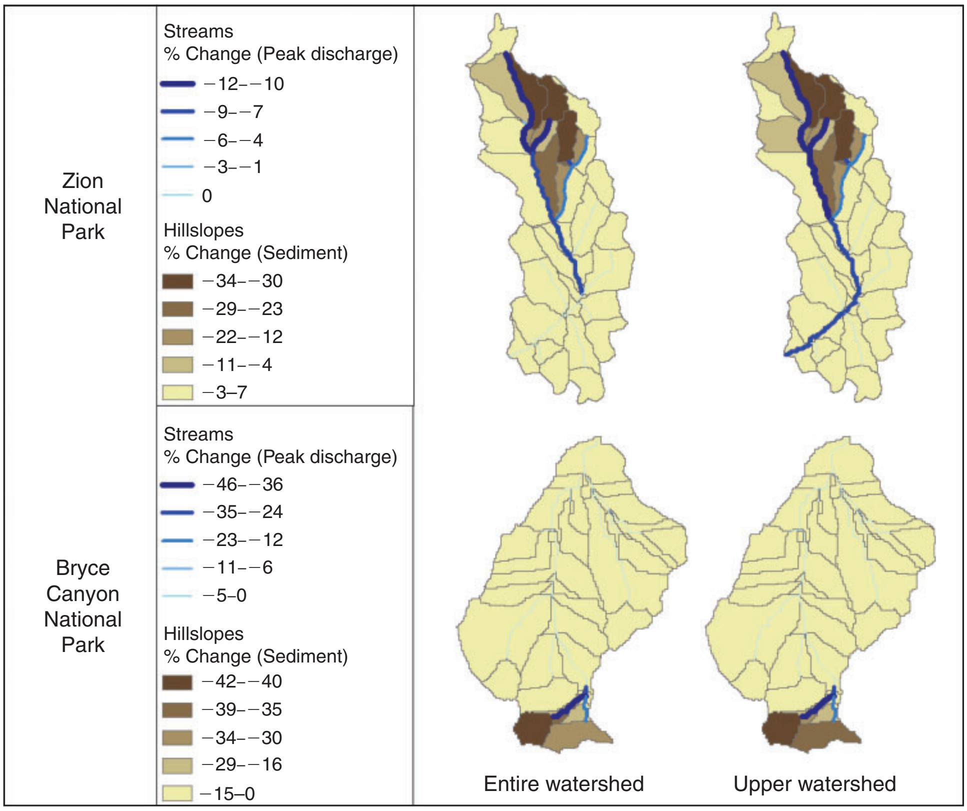

Fig. 5. Comparison of change in hydrological response between untreated and treated landscapes after entire watershed and upper watershed wildfires.

Post-wildfire hydrological response

In the entire watershed wildfire scenarios, fuel treatments had a larger effect on stream reaches just downstream of the treatment areas than at the watershed outlets (Fig. 5). In Zion's Wildcat Canyon just below the treatment area, the prescribed fire reduced peak flow by 7% whereas change was negligible in the slot canyon at the watershed's outlet (Fig. 6; Table 3). In Bryce Canyon, peak flow was reduced by 34% at a trail crossing just below the mechanical thinning area, whereas the change was also negligible at the watershed outlet at the park boundary. The results from the upper watershed wildfire scenarios showed a slightly different pattern (Fig. 7; Table 3). In Zion, the prescribed fire reduced peak flow by 9% at both Wildcat Canyon and the slot canyon. However, in Bryce Canyon, the prescribed fire reduced peak flow by 50% at the trail crossing but did nothing at the park boundary.

The lack of effect at the watershed outlets for both study sites points to the importance of both treatment size and location. First, the treatments in both sites covered relatively small portions of the entire watersheds, effectively limiting the influence of the treatments at the watershed outlet. Too large a percentage of the watersheds were untreated for the treatment to show any substantial effect. Second, although total volume and sediment should not be significantly affected by treatment location, the locations of the treatments were too far upstream to affect the peak flows at the outlets. Rain that fell on the upper watersheds in both sites, including the treatment areas, did not reach the outlets until the recession limbs of the hydrographs. To have a larger effect on peak flow, treatment areas would have to be relocated to the centres or lower portions of the watersheds.

At the location directly below the Bryce Canyon treatment area, mechanical thinning reduced peak flow by a greater percentage than the prescribed burn. This difference may be due to the lower rainfall total and maximum rainfall intensity exhibited by the event at Bryce Canyon. Percentage change tends to be accentuated at lower absolute values, so a slight absolute change may appear as a large relative change. In absolute terms, the prescribed burn reduced peak flow by 0.23 $m^3 s^{-1}$ below the treatment area, whereas the mechanical thinning reduced it by only 0.0023 $m^3 s^{-1}$.

Caveats of the modelling approach

Despite the success of developing this modelling approach linking fuel treatments to post-fire runoff and erosion, several limitations and sources of error exist. One is the variable quality of input data. For example, the level of detail included in NTLL (complete stands for the entire contiguous US), combined with this layer's integral role in determining tree mortality, make the accuracy of this layer critical to this modelling approach due to the sensitivity of KINEROS2–AGWA to fire severity. However, precision testing done by Drury and Herynk (2011) indicated that only 27% of pixels matched the dominant species of independent field plots at their study location. Further, it is unknown if NTLL will ever be updated in the manner of LF to provide

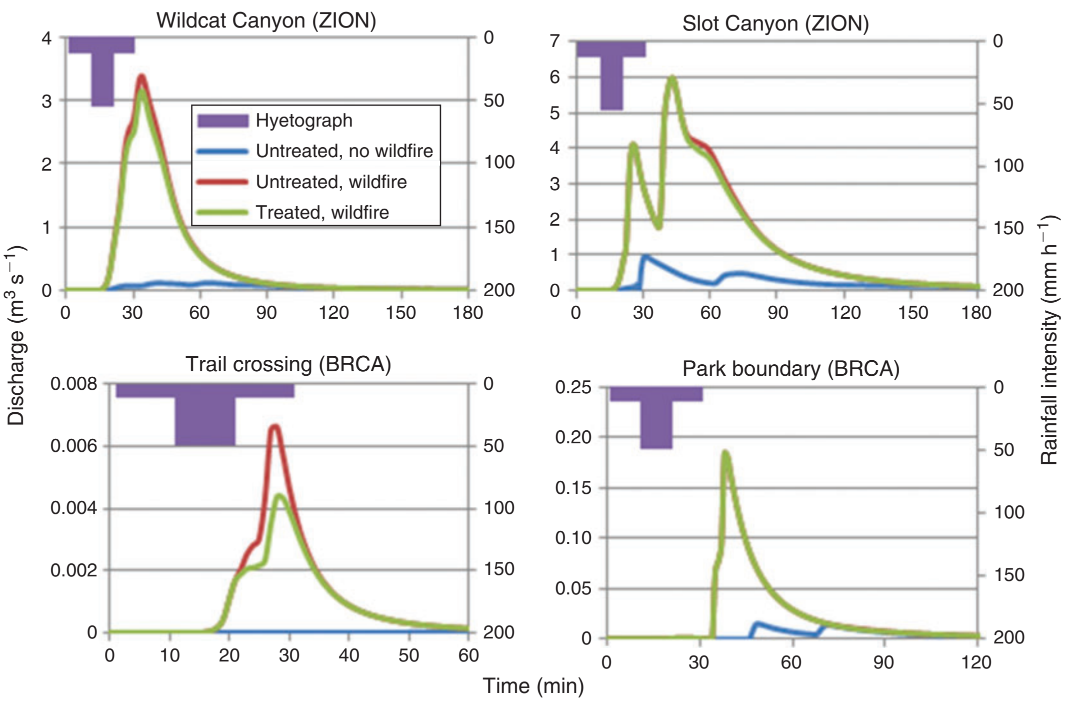

Fig. 6. Hydrographs and hyetographs illustrating design storm rainfall and watershed response after entire watershed wildfires. Hydrographs, which show the discharge over time in a stream channel, correspond to the primary (left side) *y*-axes. Hyetographs, which show the rainfall intensity over time for the design storms, are inverted and correspond to the secondary (right side) *y*-axes. Hyetographs are shown as solid to indicate that rainfall was applied continuously throughout the storm.

current data. Given these deficiencies, it would be preferable to utilise local tree list data in lieu of the NTLL if available. Nonetheless, in the absence of local data containing all the necessary parameters to run FOFEM, NTLL is currently the best default alternative on a national scale. In addition, recent studies have explored the option of classifying fuels through use of light detection and ranging (LiDAR). Airborne LiDAR scanners may be a more accurate way to classify fuel characteristics such as canopy height, canopy bulk density and canopy base height (Erdody and Moskal 2010). LiDAR may also have the capability of providing complete and accurate tree lists over entire landscapes (van Leeuwen and Nieuwenhuis 2010; Swetnam and Falk 2014).

The assumption made in this modelling approach that smaller trees have higher differential mortality is another possible source of error. This assumption is simplistic, as bark thickness, crown base height, tree species, tree vigour and fire behaviour all play a role in tree mortality (Ryan and Reinhardt 1988; Lutes 2013; van Mantgem *et al.* 2013*a*, *b*). However, the assumption was made for this modelling methodology to limit the approach's complexity.

Another source of error within the KINEROS2–AGWA model comes from the alterations AGWA makes to KINEROS2 input parameters based on fire severity. Currently, AGWA modifies only the land cover input layer, changing percentage cover and hydraulic roughness as a function of the level of burn severity. Interception is altered as a function of canopy cover change. Hydraulic conductivity is altered solely based on the drop in percentage cover based on results from rainfall simulation experiments conducted under a variety of cover conditions (Goodrich 1990). Hydrophobicity, ash residue and effects of the collapse of soil structures on hydraulic conductivity are not considered, as this information is not available from the non-field verified Burned Area Reflectance Classification (BARC; DeBano *et al.* 1998; Moody *et al.* 2013). Ideally, field or remotely sensed indicators of hydrophobicity, ash accumulation and soil structure change could be incorporated into AGWA to further refine post-fire soil parameter estimates. During 2014 BAER deployments, post-fire field observations have been used to modify hydrologic conductivity infiltration parameters in AGWA simulations that were initially based solely on the non-field-verified BARC maps. Further, the parameter changes selected for KINEROS2 inputs are based only on one post-fire watershed in New Mexico (Canfield *et al.* 2005). Parameter changes could vary in different locations with fires of different severities and watersheds with different characteristics. Current efforts are underway to identify and collect high-quality rainfall, runoff, and if available, sediment observations from watersheds before and after fire, to add to the analysis presented in Canfield *et al.* (2005) to determine more robust rules for altering post-fire model parameters. If remote sensing methods could reliably estimate areas of hydrophobicity and significant ash residue, more informed methods to alter post-fire KINEROS2 model estimates using this information would be warranted.

Implications for use by land managers

The first step in deciding if this modelling approach is viable for use by land managers is to verify the accuracy of modelled results. The accuracy of the results from FOFEM–WFAT was

Table 3. Results from KINEROS2/AGWA simulations

Entire watershed wildfire				
Prescribed Fire (Zion)				
	Wildcat Canyon		Slot Canyon	
	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)
Untreated, no wildfire	0.12	21.49	0.97	68.23
Untreated, wildfire	3.39	1473.61	5.98	804.22
Treated, wildfire	3.16	1374.11	5.98	804.10
% change	−6.88	−6.75	0.00	−0.02
Mechanical thin (Bryce Canyon)				
	Trail crossing		Park boundary	
	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)
Untreated, no wildfire	0.000087	0.0012	0.014	0.83
Untreated, wildfire	0.0067	0.16	0.19	28.63
Treated, wildfire	0.0044	0.09	0.19	28.63
% change	−34.46	−44.68	0.00	0.00
Upper watershed wildfire				
Prescribed fire (Zion)				
	Wildcat Canyon		Slot Canyon	
	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)
Untreated, no wildfire	0.12	21.49	0.97	68.23
Untreated, wildfire	3.25	1381.76	3.24	324.43
Treated, wildfire	2.98	1272.44	2.98	293.27
% change	−8.48	−7.91	−7.98	−9.60
Mechanical thin (Bryce Canyon)				
	Trail crossing		Park boundary	
	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)	Peak flow ($m^3 s^{-1}$)	Sediment ($kg s^{-1}$)
Untreated, no wildfire	0.000087	0.0012	0.014	0.83
Untreated, wildfire	0.0069	0.17	0.029	2.33
Treated, wildfire	0.0046	0.094	0.029	2.34
% change	−34.19	−42.99	0.00	0.16

determined by comparing the KSI severity distribution of the untreated wildfires to the burn severity distributions of the actual wildfires they were designed to emulate (Table 4). The burn severity distributions of the actual wildfires were obtained from the Monitoring Trends in Burn Severity (MTBS) database, which relies heavily on satellite imagery to classify burn severity. Therefore, it is inherently different from the KSI used by WFAT; nonetheless, comparing the two can be useful for analysing how well FOFEM–WFAT matches actual wildfires. The untreated entire watershed wildfire at Zion matched the severity distribution of the Kolob Fire very closely, having the same amount of unburned and high severity area while underestimating moderate severity and overestimating low severity by 5%. The untreated entire watershed wildfire at Bryce Canyon did not match the severity distribution from the Bridge Fire quite as well; the modelled fire overestimated moderate severity by 18% and underestimated high severity by 15%. Nonetheless, the unburned and low severity modelled fire distributions at Bryce Canyon were within 4% of the Bridge Fire properties. Considering that weather inputs from the Kolob and Bridge fires were used for the model wildfires at Zion and Bryce Canyon, it is encouraging to observe that the severity distributions of the two modelled wildfires match those of the actual wildfires relatively well.

To determine the accuracy of post-fire peak discharge modelled by KINEROS2–AGWA, the change from pre- to post-fire peak discharge modelled by KINEROS2–AGWA in this study can be compared with measured increases from actual pre- and post-fire flood events. Neary *et al.* (2005) recorded several such events, in which post-fire peak discharges increased by a factor of 1.4–2232 times in the western US. Untreated post-fire peak discharges recorded in this study increased from pre-fire peak discharge by factors ranging between 2 and 79. In order to compare KINEROS2–AGWA modelled sediment yield, results can be compared with total storm sediment yields reported by Robichaud *et al.* (2008). That study observed post-fire sediment yields between 0 and 19.8 Mg ha^{-1}. Storm total sediment yields in this study ranged between 0.005 and 1.81 Mg ha^{-1}. Although this comparison is limited by the differing study site locations and fire severity distributions, it shows that modelled sediment yields were within a realistic range.

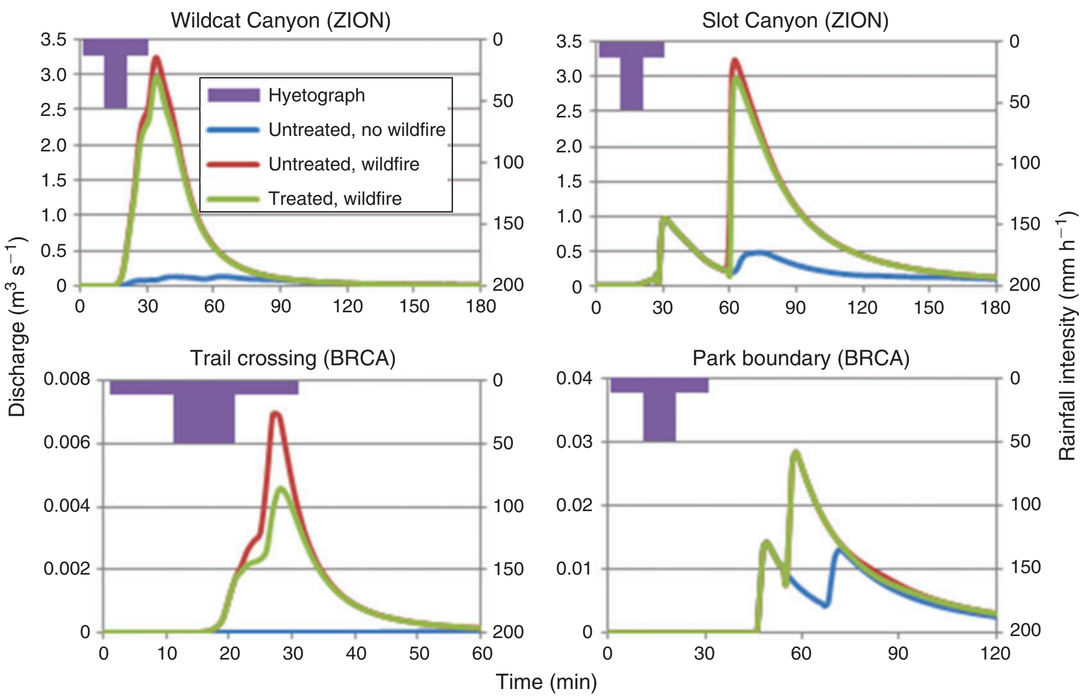

Fig. 7. Hydrographs and hyetographs illustrating design storm rainfall and watershed response after upper watershed wildfires. Hydrographs, which show the discharge over time in a stream channel, correspond to the primary (left side) *y*-axes. Hyetographs, which show the rainfall intensity over time for the design storms, are inverted and correspond to the secondary (right side) *y*-axes. Hyetographs are shown as solid to indicate that rainfall was applied continuously throughout the storm.

Table 4. Comparison of KSI severity distributions for entire watershed wildfires at Zion and Bryce Canyon national parks with the burn severity distributions from the actual wildfires they were meant to emulate

Severity distributions for the Kolob and Bridge fires were obtained from Monitoring Trends in Burn Severity (WLC 2014)

	Zion		Kolob Wildfire		Bryce Canyon		Bridge Wildfire	
	ha	%	ha	%	ha	%	ha	%
Unburned	347	15%	1029	15%	44	20%	1223	24%
Low	935	41%	2361	34%	64	30%	1460	29%
Moderate	828	36%	2857	41%	92	42%	1212	24%
High	187	8%	643	9%	17	8%	1170	23%

Almost no studies have attempted to determine the change in runoff and erosion from wildfire on an untreated to a treated landscape. A significant obstacle to completing a study of this nature is the limited availability of high-resolution rainfall observations, which are essential to validating this approach. Although Wohlgemuth *et al.* (1999) provides such an opportunity, the results mentioned are longer-term sediment yields, rather than event-based yields. This makes it impossible to compare those results with KINEROS2 results. However, this study's results are consistent with the general trends observed: fuel treatments mitigated wildfire severity and therefore post-fire runoff and erosion.

There are many potential uses of this linked modelling approach. Land managers could use these tools to decide which fuel treatments or combination of treatments lower post-wildfire runoff and erosion to an acceptable threshold. This would allow them to better protect values at risk downstream of potential wildfire locations. Given the limitations noted above it is best currently to use the modelling approach to spatially compare the relative change of various scenarios in an attempt to identify the best fuel treatment type and its location. If multiple locations are being considered for fuel treatments, scenarios could be evaluated with this modelling approach to determine the best locations to meet management objectives and prioritise where fuel treatments should be placed.

Conclusion

The modelling approach described in this study provides a viable option for landscape scientists, watershed hydrologists and land managers hoping to predict the effect of fuel treatments on post-wildfire runoff and erosion, despite several limitations and potential sources of error. Several uses of the model exist, from measuring how well treatments mitigate the hydrologic response following wildfire, to determining the best spatial location of the treatments. It is recommended that the modelling approach be used as a relative change tool, rather than a tool to predict absolute values of peak flow and sediment yield.

The results of the case studies employed here suggest that the magnitude of the effect of a fuel treatment on post-wildfire hydrological response mitigation varies according to several factors, including the size of the wildfire and the size of the fuel treatment. It was not the objective of this case study to decide whether the proposed fuel treatments in Zion and Bryce Canyon national parks were worthwhile management options or under what circumstances they should be implemented. This is especially true since the main goals of park staff in both cases were to reduce fire behaviour and improve forest health, not to mitigate post-fire hydrological response. This study aimed primarily to demonstrate a novel linked model approach, and secondarily to give park managers more information and data to make a more informed management decision.

Several items should be addressed to further streamline this modelling approach and reduce potential limitations and error. Within the WFAT framework, the most important area to address is the creation of a publicly available national tree list layer. The functionality of the tree list database could be improved as well to include automated updates to account for the changes caused by fuel treatments. Better ways to map forest fuel characteristics at a landscape level must be explored as well, such as the use of LiDAR.

Within the AGWA framework, post-fire alterations of KINEROS2 inputs should be further researched. Parameter changes should be made according to relationships that are drawn from a larger number of actual wildfires and should include further soil alterations due to ash, hydrophobicity and soil structure change. This would decrease potential sources of error in hydrological modelling and increase model sensitivity to wildfire effects.

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